GEOLOGIC SEQUESTRATION IN WYOMING – FILLING UP THE "BIG EMPTY"

Dag Nummedal
nummedal@uwyo.edu
http://www.ieronline.org
307.766.2773
Institute for Energy Research
Department of Geology and Geophysics
University of Wyoming
Laramie, WY 82071

Julio Friedmann
juliof@geol.umd.edu
http://www.geol.umd.edu
Department of Geology
University of Maryland
College Park, MD 20742

Vicki Stamp
vicki.stamp@rmotc.doe.gov
www.rmotc.com/index.html
Rocky Mountain Oilfield Testing Center
Casper, WY 82601

Abstract

The reduction of greenhouse gases with the goal of mitigating global warming may generate major economic benefits to many of America's sparsely settled regions, in particular those with extensive sequestration sinks, such as depleted oil and gas reservoirs, unmineable coal seams, saline aquifers, and oil shales. Sequestration potentials in croplands, range, and forest ecosystems add further sequestration value to these same regions because of the abundant open space. Wyoming, the most 'empty' of all US states, and the surrounding Rocky Mountain region with similar geology and ecosystems, provide a natural focus for the emergence of a major US sequestration industry.

Introduction

The recognition of serious risks associated with anthropogenic greenhouse gas emissions has resulted in a broad-based desire to reduce global and national emissions of greenhouse gases (GHG), especially CO_2. This desire has prompted the investigation into carbon sequestration on the whole, including terrestrial, ocean, and geologic sinks (US DOE, 2002; Ekmann and Feeley, 2002). The geology of the Rocky Mountains, as well as their terrestrial ecosystems, makes them an outstanding candidate for carbon storage in many forms (Friedmann, 2003). We believe that the chance of success for storing large volumes of carbon in the Rockies is exceptionally high.

To encourage Wyoming and surrounding states to move towards leadership roles in this new economic activity, a group of scientists and engineers at universities and technology companies in Wyoming, Colorado, and Utah have formed a Carbon Utilization and Storage Partnership

(CUSP). CUSP is a compact between the leading research institutions and state agencies in these three states and numerous private and federal partners. The partnership is designed to be a collaborative effort between the Federal Government – represented by national labs and testing facilities; state governments – represented by Geological Surveys and GIS agencies, oil and gas companies committed to CO_2-enhanced oil recovery in the region, coal companies, the major utilities, as well as agricultural R&D institutions, outreach agencies, and environmental NGOs.

The long-term goals for CUSP are to reduce the emissions of greenhouse gases (GHGs) from the region's many power plants and other industrial facilities and to use the primary GHG – CO_2 – as a resource for regional industrial growth and environmental enhancement. CO_2 becomes a valuable resource when it is used in the deep subsurface for enhanced oil, gas, and coal bed methane production, and in the shallow underground to increase the carbon content of the region's soils.

In addition to help solving the major global environmental problem, there are potentially large regional economic gains to be made from such actions. In the near term, the benefits will primarily accrue to the agricultural sector. Soils with higher carbon contents enhance crop yields, sustain a growing biomass, healthier forests, and reduce run-off and erosion. The mid-term benefits will accrue mostly from the enhanced oil recovery industry (Nummedal et al., 2003). The long-term gains are probably best expressed in an open letter to the premier of Alberta by T. Homer-Dixon (2002). His concluding paragraph reads:

> "All the basic technology to do this [CO_2 utilization and storage] is available, but there are, inevitably, lots of technical details to be worked out. However, the spoils will go to those who work out these details. History shows that great technological transitions generate extraordinary profits for the people, companies, and countries that lead the way."

The primary objectives of the Carbon Utilization and Storage Program are to analyze the synergy between enhanced oil recovery and reductions of CO_2 emissions, and to explore a range of new options for utilization of the state's valuable CO_2 resource. We expect that, as a 'spin-off' of this program, numerous new technologies for separation, transportation, injection, and utilization of CO_2 will emerge – technologies that some companies may choose to utilize in Wyoming operations and/or commercialize for global sales.

The Wyoming CO_2 Budget

Does WY and the region have sufficient CO_2 to make this vision a reality? Yes. The Wyoming Geological Survey (De Bruin, 2001) has completed an assessment of the state's CO_2 requirements for enhanced oil recovery in all potential candidate fields. De Bruin concludes that EOR might increase the state's cumulative oil production by 0.4 to 1.2 BBO, with an input of somewhere between 2.4 and 12 TCF of CO_2. Total statewide underground reserves of CO_2 are about 55 TCF (3.6 G tons of CO_2). Additionally, the current Wyoming power plants are currently permitted for a release of about 1.7 TCF of CO_2 (98 MM tons per year). Actual current release rates are somewhat less than this. The day technology is in place to harness this resource for industrial use, Wyoming will have crossed the threshold into the "new energy economy".

Does the WY CO_2 flux matter on a global scale? Yes, because we are a large energy producer and a 'world class' CO_2 factory. Wyoming releases 60 times as much carbon into the air, per capita, as does the world's population overall. There are good reasons for this; nevertheless, it puts the state in a great position to utilize CO_2 for local industrial growth and to take on a responsible leadership role in the reduction of global greenhouse gas emissions to the atmosphere.

Wyoming's New CO_2 Infrastructure

Anadarko's acquisition of Howell Petroleum's Salt Creek Field and the rights to extend the CO_2 pipeline from Lost Soldier Field to the edge of the Powder River basin, fundamentally changed the 'landscape' for CO_2 related industries in Wyoming (Figure 1). The pipeline capacity will be sufficient to carry 91 BCF of CO_2 per year, which is nearly half of the total current production at ExxonMobil's LaBarge field, the source of the gas. Half of this volume (125 MMCF/d or 45 BCF/y) is earmarked for enhanced oil recovery use at the Salt Creek oil field; the other half may go to other fields in the area. Also, Anadarko will build a 'spur' CO_2 pipeline to its Patrick Draw field in the Washakie basin (eastern part of Greater Green River basin in Figure 2). In addition to these new initiatives, CO_2 enhanced oil recovery and associated sequestration will continue, yet at diminishing rates, at Rangely, Lost Soldier, and Wertz fields where such activity has been ongoing since the late 1980s. As demonstrated in Figure 3, the use of CO_2 for enhanced oil recovery in many Rocky Mountain oil fields is a well-proven technology with large sequestration potential as well as economically attractive increase in field production. Stevens et al. (1999) have calculated that since the beginning of CO_2-EOR, the three Rocky Mountain oil fields listed above have already sequestered a total of 710 BCF (39.5 MMtons) of CO_2.

Regional CO_2 Sources

A large number of high-volume CO_2 point sources exist within the region (Figure 1). These are dominated by electrical production, mostly coal-burning power plants. These plants have a variety of configurations and ages, but several of them produce enormous emission volume, including Jim Bridger (19 MM tons CO_2/yr) and Laramie River 1, 2 and 3 (together: 15 MM tons) in Wyoming; Hunter and Huntington (together: 17 MM tons) and Intermountain (15 MM tons) in Utah; Craig in Colorado (10 MM tons); and the Colstrip power plant in the Powder River basin part of Montana (17 MM tons). Overall, fully 50% of the coal-fired power plants in the American West lie within the CUSP partnership area.

The existing network of CO_2 pipelines lies within a few kilometers of many of these plants (Figure 1). Most plants are owned and operated by CUSP members (PacifiCorp, Basin Electric, Xcel, Platte River, Tri-State). Their participation helps ensure proper characterization of the facilities and timely assessment of their sequestration options.

Economies of scale apply to the assessment and implementation of many technologies, including CO_2 separation from flue gas, compression, transportation, and utilization of this gas for EOR, R&D needs for efficient use of CO_2 in enhanced CBM production, CO_2 sequestration in saline aquifers, and potential design and construction of zero-emissions power plants in the region over the next decade (e.g., the "FutureGen" power plan initiative). Life-cycle assessment of aging power plants (such as Dave Johnson, WY – 7.3 MM tones CO_2/yr) and a consideration of coal-plant vintages and implications for plant replacement is an essential step in the emergence of a regional sequestration strategy (Dahowski and Dooley, 2002; Dooley and Dahowski, 2002).

There are also other industrial CO_2 sources in the Rockies. These include gas-processing facilities (Shute Creek Plant in WY, 9.7 MM tons CO_2/yr, Lost Cabin Plant in WY, 1.9 MM tons CO_2/yr), refineries (Sinclair in WY; Vanco and Conoco in Commerce City, CO; Tesoro and ChevronTexaco in Salt Lake City, UT), cement plants, and other sources. The relatively pure refinery CO_2 is a particularly low-cost commodity (Simbeck and Johnson, 1999), which may increase its potential utility for storage. The CO_2 from gas processing is natural, and some is already used for regional EOR activities, yet much is currently vented but could be stored in near-by sinks. In addition to CO_2, significant volumes of point-source methane are associated with coal mining in the Rockies, mostly in the Powder River basin.

Although not a densely populated region, the growth of several large Rocky Mountain cities has resulted in significant distributed urban CO_2 flux. The greater Denver area is the largest with a population of 2.4 million people. Rapid growth, over 29% since 1990, has resulted in a significantly increased CO_2 flux. Similarly, Salt Lake City has seen great recent growth, with attendant concern over emissions.

There are no major net terrestrial CO_2 sources in the region, and crop- and rangeland soils as a whole are probably carbon-neutral or a small sink at the present time (Eve et al., 2002). Episodic events, such as the big wildfires in Colorado in 2002, can represent a significant transient source of CO_2. However, forests overall are a net C sink. The non-CO_2 greenhouse gases from agricultural sources in the region are CH_4 from livestock and N_2O associated with high fertilizer N inputs in irrigated, intensively cropped areas.

Regional Geologic Sequestration - Principles and Potential

Geological sequestration options include large, partially depleted oil and gas fields (Figure 1), extensive saline aquifers in large, intermontane sedimentary basins, vast coal beds, and organic-rich lacustrine shales (Figure 2). All these sinks lie close to large coal-burning power plants and a growing, regional CO_2 pipeline transportation network.

The regional geology involves two linked but separate candidates for geological carbon storage and utilization. The first is porous rock bodies, those in depleted oil and gas fields (EOR targets and permanent storage) and saline aquifers. The second class involves organic minerals bound in unmineable coal seams and oil shales. The uncertainty over total storage capacity, especially in the second class of targets, is quite large (US DOE, 1999) and much work needs to be done to quantify such sequestration potentials in the Rocky Mountains. Similar reservoir characteristics for both EOR and saline aquifer targets, commonly involving the same stratal units (Hovorka et al., 2000;Wray et al., 2002; De Bruin et al., 1993), provide an economy of scale in applying many of the same technologies and expertise for assessment and storage.

It is probable that the CUSP Region has the largest potential for *coal* storage anywhere in the world (Ayers, 2002). Wyoming's annual coal production for export is >350 MM tons (www.eia.doe.gov). The Powder River Basin (PRB) ranks second in US CBM production, and the Greater Green River basin (GGRB) has the greatest US potential for CBM. The San Juan basin in southern Colorado and northern New Mexico is the largest US-CBM producer.

Sequestration and EOR Potential of Depleted Oil and Gas Fields and brines –. The physics and chemistry of storage in these sinks are governed by fluid displacement, CO_2 miscibility (Jessen et al, 2001), and reservoir cap-rock geology (Johnson et al. 2001; Friedmann and Nummedal, 2003;

Klusman, 2002). Fluid displacement is governed by reservoir thickness, porosity, permeability, and injectivity (Islam et al, 1999; Montgomery et al., 2000; Odam et al., 2002). CO_2 miscibility is governed by gas solubility, pore fluid chemistry, injection pressure, and temperature.

Importantly, many candidate fields for EOR occur within the region at various stages of development. They vary from Rangely (>15 years CO_2 injection), to Salt Creek (planned injection January 2004), to potential development. This demonstrates that commercial success in past EOR projects has encouraged new entrants into this industry, and that further EOR development in the region is likely to accelerate. Moreover, EOR is further stimulated by the growing recognition that the economics of reserves addition in the mature basin onshore US now favors the use of CO_2 enhanced oil recovery as compared to the 'traditional' steps of exploration, development and production (Figure 4; Bradley, 2001). Finally, in a recent study of a large number of oil fields onshore US and in Russia, Attanasi et al. (1999), found that 'proved reserves' (oil producible at economic rates with existing technology) continuously increase with the age of an oil field.

Regional governmental and industrial entities are currently being energized to vigorously pursue EOR growth opportunities in the Rocky Mountains (Nummedal et al., 2003). On case study is Burlington Resources' consideration of using their current CO_2 production at the Lost Cabin plant for EOR in other reservoirs in their own field or, alternatively, extend a local CO_2 pipeline network to nearby fields on the Casper Arch. As this is being written, negotiations have just started between a major utility and a mid-size Wyoming independent to explore buying carbon offsets through support of EOR development. The partnership hopes to encourage many more such developments.

As mentioned above, Anadarko has initiated an enhanced oil recovery project at Salt Creek Field in Wyoming (Figure 1), which will be the largest new geological sequestration project in the region. Injection rates at the start of the project will amount to 2.5 million tons of CO_2 being injected per year (Anadarko, 2003, project web site). This amounts to as much as 2% of Wyoming's total carbon release rate (from power plants and industrial operations), which compares favorably to the injection rate at the Weyburn field in Canada of about 1.8 million tons of CO_2 per year.

Some of the injected CO_2 is recirculated during oil production (because of the economic driver to reduce the cost of CO_2), captured at the production well, and reinjected back into the reservoir. By the time the entire EOR project at Salt Creek comes to completion, Anadarko expects to have sequestered about 30 million tons of CO_2, or about 75% of the total amount of CO_2 sequestration that has taken place to date in the combined Rangely, Lost Soldier, and Wertz fields.

Depleted gas fields also present a special case. Within Wyoming, in particular, there are many large fields that are nearing the point of final blow-down. Some of these fields are receiving methane for short-term market storage and to prevent reservoir damage (US DOE, 2002). These provide a window of opportunity for repressurization with CO_2.

Many of the formations within the Rocky Mountains region also hold brines at depth. These saline aquifers occur in a variety of structural and stratigraphic configurations. In addition, there are local and regional potentiometric gradients that may affect the regional flow of brines and other fluids. Saline aquifers do not hold hydrocarbon accumulations for long periods of time, thus the risk of potential CO_2 leakage is significant. The risk can be reduced and calibrated using a combination of structural and stratigraphic tools, including fault-seal and fracture analyses, closure mapping, and targeted searches for stratigraphic thief zones. Importantly, modeling of groundwater flow in the White Rim Sandstone in Utah shows transport rates sufficiently slow to retain injected CO_2 for hundreds of years (Rick Allis, personal communication, 2003).

Sequestration Potential of Unmineable Coals and Oil Shales –. The physics and chemistry of these sinks are dominated by CO_2 adsorption onto organic mineral surfaces (Reznik et al., 1984; Pashin, 2003). This process varies with coal rank and mineralogy (Byrer and Guthrie, 1997). Within the CUSP region, sub-bituminous and bituminous coals of various compositions occur in great abundance (Figure 2). The diverse compositions present a unique opportunity for a national coal sequestration study site, where the many issues related to the effects of cleat-dominated permeability, mineral surface area and coal petrography could be addressed (Reeves, 2001).

The Rocky Mountains region also contains the largest and best-studied oil shale accumulations anywhere in the world (Laramie Energy Tech Center, 1980). The main target is the Green River Formation, which occurs in the Greater Green River, Piceance, and Uinta Basins (Figure 2). The oil shales have total organic carbon (TOC) values between 6% and 25% (Robinson and Cook, 1975). The organic carbon kerogen has undergone recrystallization into organic minerals (macerals) similar to those of coals. Like coals, the permeability is controlled by fracture density, and like coals the organic minerals should adsorb CO_2 and release hydrocarbons. This potential target capacity is difficult to assess due to lack of previous scientific study in terms of carbon storage mechanisms and potential.

National Geologic Carbon Storage Test Site at Naval Petroleum Reserve # 3

It is rare that nature, industrial schedules, and public policy imperatives converge as strongly as they currently do on the SW flank of the Powder River Basin in Wyoming. Two large, anticlinal oil fields, Salt Creek (Wyoming's largest) and Naval Petroleum Reserve no. 3 (Teapot Dome), lie side by side along the same structural trend. As just mentioned, Salt Creek is scheduled to become Anadarko's largest CO_2-driven enhanced oil recovery operation, with injection scheduled to start in January 2004. Immediately adjacent to the southeast lies the center of NPR-3, DOE's oil field operated by the Rocky Mountain Oilfield Testing Center (RMOTC), and dedicated to testing, evaluations and R&D – ideally suited for a major, focused R&D mission.

The two fields produce from the same nine stratigraphic intervals ranging in depth from 500 to 5500 feet with a combined volume of more than 2 billion barrels of OOIP. The key intervals include almost all of the major producing units within Wyoming and Northern Colorado, and have porosities, permeabilities, and compositions similar to the majority of Rocky Mountain depleted oil and gas fields and saline aquifers.

These fields represent a singular opportunity to create a world-class EOR and sequestration R&D pilot project in the US. The unique juxtaposition of private and public facilities makes it possible to rigorously evaluate the synergies between the use of CO_2 for enhanced oil recovery purposes and for sequestration. Optimization for one or the other may require differences in the timing of CO_2 flooding relative to other recovery approaches, the use of WAG (Water Alternating with Gas), and the potential for storage in and monitoring of deeper saline aquifers that are not hydrocarbon bearing.

Conclusions

Because of the dispersed population and abundant depleted oil and gas field, coal beds, regional saline aquifers, and oil shales, Wyoming and the surrounding Rocky Mountain states are beginning to emerge as the natural focus for a major US sequestration industry. To assist the region to move towards a leadership role in this new economic activity, a group of scientists and engineers in Wyoming, Colorado, and Utah – together with numerous state, federal and private partners – have formed a Carbon Utilization and Storage Partnership (CUSP). The long-term goals for CUSP are to reduce the emissions of greenhouse gases (GHGs) from the region's many power plants and other industrial facilities and to use the primary GHG – CO_2 – as a resource for regional industrial growth and environmental enhancement.

In the near term, most sequestration will occur through the growth of a regional enhanced oil and gas recovery (EOR) industry, built around a growing CO_2 pipeline network. Fields suitable for EOR occur within the region at various stages of development. They vary from Rangely (more than 15 years CO_2 injection), to Salt Creek and Patrick Draw (planned injection to start in January 2004), to potential development. This history demonstrates that commercial success in past EOR projects has encouraged new entrants into the industry, and that further EOR development in the region is likely to accelerate. Moreover, EOR is further stimulated by the growing recognition that the economics of reserves addition in the mature basins onshore US now favors the use of CO_2 enhanced oil recovery as compared to the 'traditional' steps of exploration, development and production.

To further accelerate these encouraging trends, we recommend the development of a major national geological CO_2 sequestration test site at Naval Petroleum Reserve no.3 (Teapot Dome), an eminently suitable field located at the heart of the Rocky Mountains oil and gas province.

References Cited

Attanasi, E.D., Mast, R.F., and D.H. Root, 1999, Oil and gas field growth projections – wishful thinking or reality: *Oil and Gas Journal*, 97:14, p.79-81.

Ayers, W.B., 2002, Coalbed gas systems, resources, and production and a review of contrasting cases from the San Juan and Powder River basins, AAPG Bulletin, v. 86, p. 1835-1890.

Bradley, R.T., 2001, CO_2 breathes new life into old fields: *The American Oil and Gas Reporter*, March 2001.

Byrer, C.W., & Guthrie, H.D., 1997, Assessment of world coal resources for carbon dioxide (CO_2) storage potential – while enhancing potential for coal-bed methane, *in* Remier et al. (eds.), Greenhouse gas mitigation technologies for activities implemented jointly, Conf. Proc., Vancouver Canada, p. 573-576.

Dahowski, R.T., and Dooley, J.J., 2002, Carbon management strategies for existing U.S. generation capacity: A vintage based approach, GHGT-6 Conf., Kyoto, H4-2.

De Bruin, R.H., 2001, Carbon dioxide in Wyoming, Information Pamphlet 8, Wyoming Geological Survey, Laramie, WY, 11 pp.

De Bruin, R.H., C.M. Tremain, and T.C. Chidsey, Jr., 1993, Atlas of major Rocky Mountain gas reservoirs: Colorado Geological Survey MI-40, 206 pp.

Dooley, J.J., and Dahowski, R.T., 2002, Examining planned U.S. power plant capacity additions in the context of climate change, GHGT-6 Conf., Kyoto, H4-3.

Ekmann, J., and Feeley, T., 2002, Sequestration – Progress along the road mapped, US DOE, Natl. Energy Tech. Lab, www.netl.doe.gov.

Eve, M.D., et al., 2002, National-scale estimation of changes in soil carbon stocks on agricultural lands, Environmental Pollution, 116, 431-438.

Friedmann, S.J., 2003, Storing carbon in earth: Geotimes, March 2003, p. 16-20.

Friedmann, S.J., and Nummedal, D., 2003, Reassessing the geological risks of seals failure for saline aquifers and EOR projects, 2nd Annual Conference on Carbon Sequestration, Alexandria, VA (this volume).
Homer Dixon, T., 2002, Toronto Globe and Mail, October 31 issue.
Hovorka, S. D., Romero, M. L., Treviño, R. H., Warne, A. G., Ambrose, W. A., Knox, P. R., and Tremblay, T. A., 2000, Project evaluation: phase II: optimal geological environments for carbon dioxide disposal in brine-bearing formations (aquifers) in the United States: The University of Texas at Austin, Bureau of Econ. Geology, final report prepared for US DOE/NETL, contract no. DE-AC26-98FT40417, 222 pp.
Islam, et al., 1999, Potential of greenhouse gas storage and utilization through enhanced oil recovery, Final Report, SRC Publication P-110-468-C-99.
Jessen, K., L.C. Sam-Olibale, A.R. Kovscek, and F.M. Orr, Jr., 2001, Increasing CO_2 Storage in oil recovery: 1st Annual Conf. on Carbon Sequestration, NETL Conference Proceedings, Session 2A.
Johnson, J.W., Nitao, J.J., Steefel, C.I., and Knauss, K.G., 2001, Reactive Transport modeling of geologic CO_2 sequestration in saline aquifers, the influence of intra-aquifer shales and the relative effectiveness of structural, solubility, and mineral trapping during prograde and retrograde sequestration, *in*, Conf. Proceedings, 2001 Dept. of Energy Workshop on Carbon Sequestration Science, http://www.netl.doe.gov/ .
Klusman, R.W., 2002, Identification of surface microseepage at the Rangely CO2EOR project, Colorado, Geological Society of America Annual Convention, Oct., 2002 (174-10) http://gsa.confex.com/gsa/2002AM/finalprogram/abstract_38683.htm .
Laramie Energy Technology Center, 1980, A bibliography of publications dealing with oil shale and shale oil from U.S. Bureau of Mines, 1917 - 1974, The ERDA Laramie Energy Research Center, 1975-1976, and the DOE Laramie Energy Technology Center, 1977-1979; 58 pp.
Montgomery, S.L., Schecter, D.S., and Lorenz, J, 2000, Advanced reservoir characterization to evaluate carbon dioxide flooding, Spraberry Trend, Midland Basin, Texas, AAPG Bulletin, v. 84, p. 1247-1273.
Nummedal, D., Towler, B., Mason, C, and Allen, M., 2003, Opportunities and Challenges for Enhanced Oil Recovery in Wyoming. Commissioned report to the Governor of Wyoming. 30 pp.
Odam, A., et al., 2002, Effective storage capacity in aquifers, gas fields, oil fields, and coal mines, GHGT-C Conference, Kyoto, B1-6.
Pashin, J.C., 2003, Defining the supercritical carbon dioxide window for coalbed methane reservoirs in the Black Warrior Basin: Implications for carbon sequestration and enhanced CBM recovery, Abstract, AAPG Annual Convention, Salt Lake City.
Reeves, S., 2001, Geological Sequestration of CO_2 in deep, unmineable coal beds: an integrated research and commercial-scale field demonstration project, First annual conference on carbon sequestration, DOE, Washington, D.C.
Reznik, A.A., Singh, P.K., and Foley, W.L., 1984, An analysis of the effect of CO_2 injection on the recovery of in-situ methane from bituminous coal: An experimental simulation, SPE Journal, p. 521-528.
Robinson, W.E., and G.L. Cook, 1975, Compositional variations of organic material from Green River Oil Shale - WOSCO EX-1 Core (Utah): Bureau of Mines, Report of Investigations 8017, 40 pp.
Simbeck, D., and Johnson, H.E., 1999, Report on SFA Pacific gasification database and world market report, 1999 Gasification Tech. Conference, San Francisco.
Stevens, S., Kuuskraa, V., and O'Donnell, 1999, Enhanced Oil Recovery scoping study, EPRI, Final Report TR-113836, 148 pp.
US DOE, 1999, Carbon Sequestration Research and Development, Offices of Science and Fossil Energy, www.ornl.gov/carbon_sequestration/
US DOE, 2002, Carbon sequestration technology roadmap; Office of Fossil Energy & NETL, 23 pp.
US. DOE/EIA, 2002, The Basics of Underground natural gas storage, Natural Gas Division Fact Sheet, www.eia.doe.gov, 8 pp.
Wray, L.L., A.D. Apeland, H.T. Hemborg, and C.A. Brchan, 2002, Oil and gas fields map of Colorado: Colorado Geological Survey MS-33, 1:500,000 and ArcGIS shapefile.

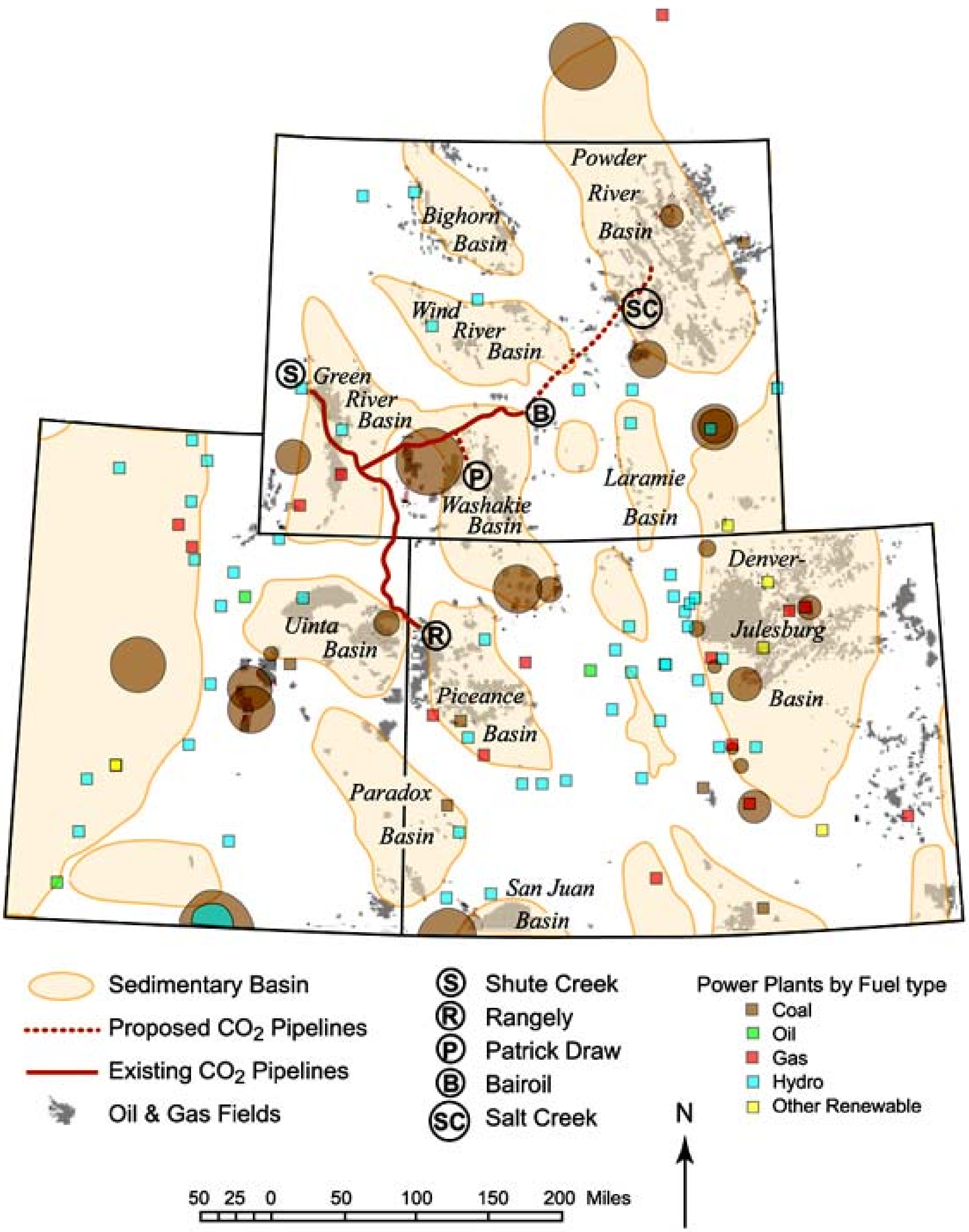

Figure 1. CO_2 pipelines, oil and gas fields, sedimentary basins and power plants in the central Rocky Mountains. Power plant 'bubble' size is proportional to emissions.

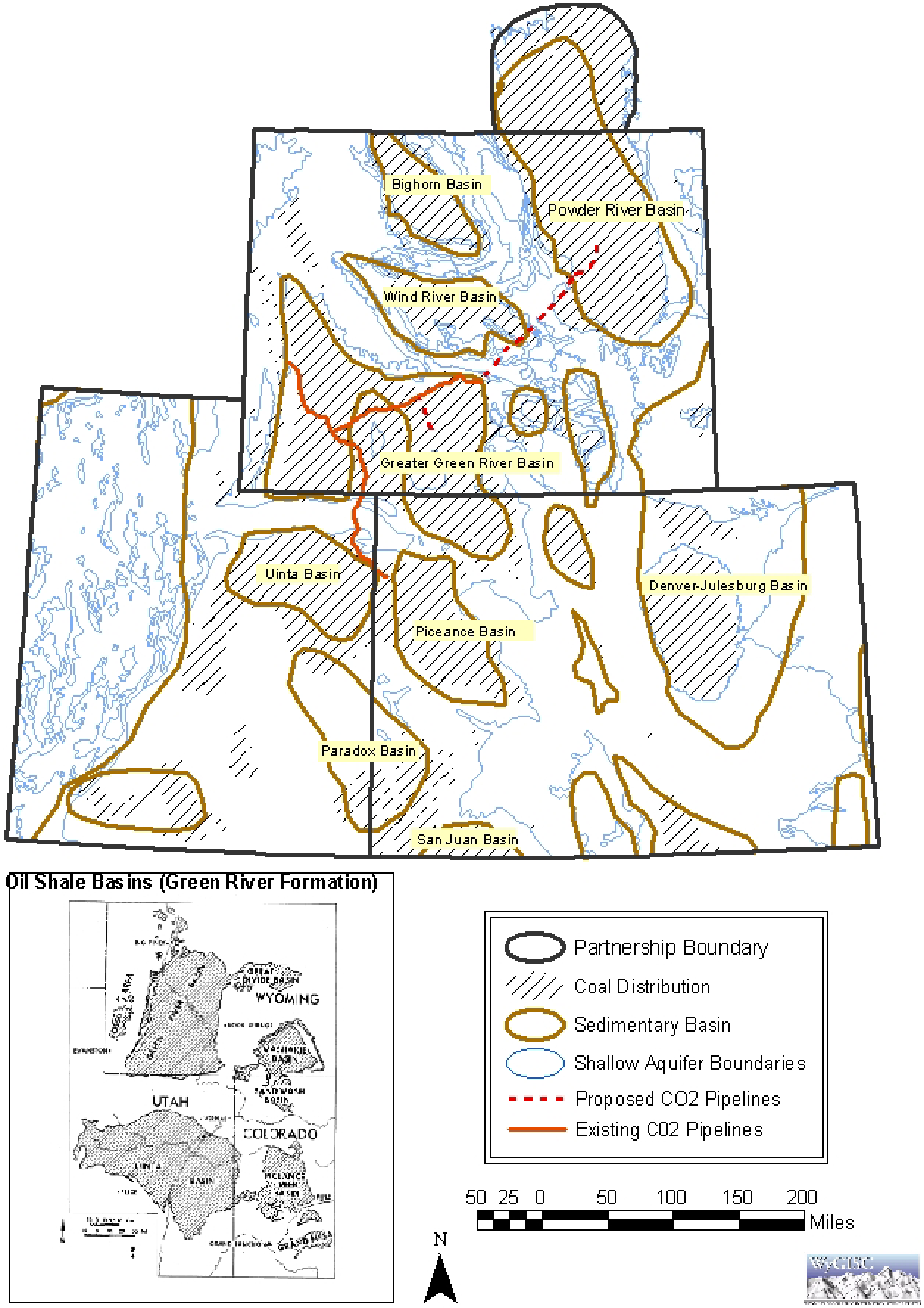

Figure 2. Distribution of coal, oil shales, and major acquifers in the central Rocky Mountain Region.

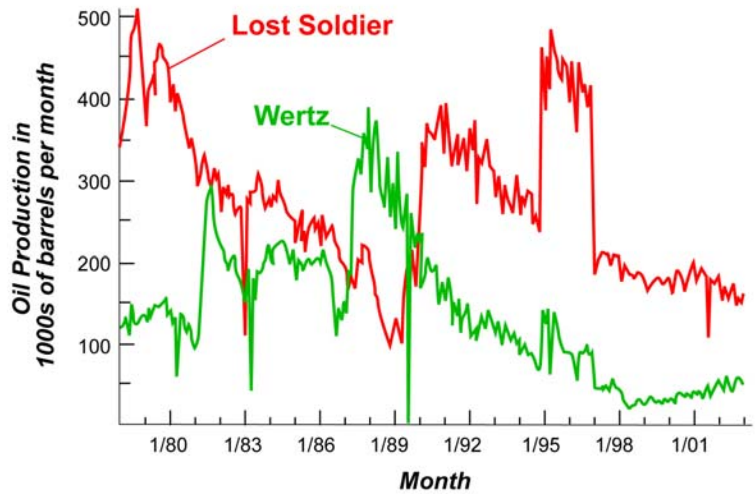

Figure 3. History of oil production at two Wyoming oil fields subject to CO-2 induced EOR since the late 1980s.

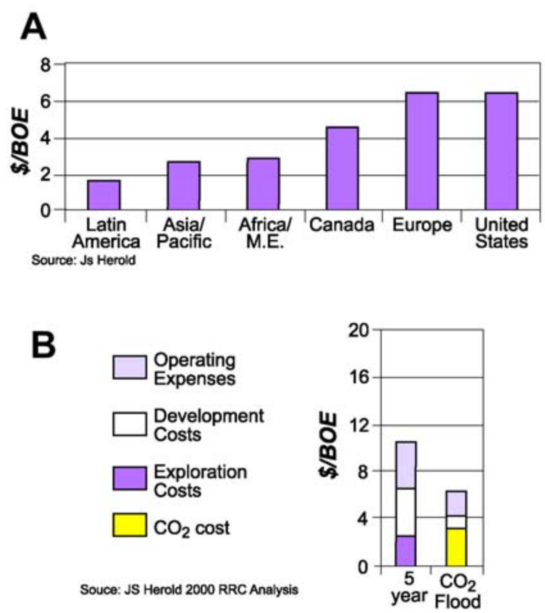

Figure 4. Comparison of worldwide finding and development cost with the cost of CO_2 miscible flooding. A: Average finding and development cost from 1995 to 1999, on different 'continents'. B: Average finding, development, and production cost in the US from 1995 to 1999 ($10, left column), compared to cost per barrel of reserves developed for CO_2 flooding ($6, right column). From Bradley (2001).